Systematic Uncertainties Developed for MINERvA

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ECT* Workshop

How do Interaction Systematics Enter?

My Emotional Support Slide

- Signal process
  - Affects efficiency
  - May effect where you even look for that process!
  - Affects detector smearing of observables
- Background Processes
  - How much do you subtract from final event sample
- Unfolding from measured to "true"
  - Underlying distribution matters!

$$\frac{d\sigma(x_t)}{dx_t} = \frac{(\mathrm{N}(x_m) - B(x_m))\, U_{mt}}{\Phi_\nu \epsilon(x_t) M \Delta x}$$

- $\mathrm{N}(x_m)$: number of events at a measured x_m
- B : Background at that x_m
- U_{mt}: Unfolding matrix for that observable
- Φ_ν : flux
- $\epsilon(x)$: efficiency
- M: must be "number of targets"

MINERvA Systematic Uncertainties

- MINERvA uses a multi-universe technique to evaluate systematics
- We re-extract cross sections using shifted universes in all steps
  - Gives us a chance to look at how uncertainties propagate through analyses
- Three categories of systematics
  - Flux (hadron production, beamline component alignment)
  - Detector (energy scale, pointing resolution, particle interactions)
  - Cross Sections
    - Nucleon-level interaction uncertainties
    - Nuclear effect uncertainties on initial state
    - Final State Interactions

$$\frac{d\sigma(x_t)}{dx_t} = \frac{(\mathrm{N}(x_m) - B(x_m))\, U_{mt}}{\Phi_\nu \epsilon(x_m) M \Delta x}$$

MINERvA's Strategy for reducing Systematic Uncertainties: "the data doesn't lie"

- Signal process:
  - Use models that are not too far from our data even if they are simply models with ad hoc weights applied to match our data ("MINERvA Tunes" starting with GENIE 2.12.6+external + internal (i.e. Low Energy beam) constraints)
- Backgrounds:
  - Use sideband techniques to constrain backgrounds before subtracting from signal region as much as possible
- Ratios:
  - Nuclear Target/Scintillator Material
  - ν_μ/ν_e and $\bar{\nu}_\mu/\bar{\nu}_e$
  - $\bar{\nu}_\mu/\nu_\mu$ Ratios

From Jeremy's talk yesterday:
Data-driven philosophy
But still try to bring new models in where we can

GENIE Systematic Uncertainties used in MINERvA for ν Interaction Uncertainties

- Sarah Henry's thesis:
- https://inspirehep.net/literature/2182242
- But you can find this list in some form in most MINERvA theses
- So how can we hope to make precision measurements when the variations that are "allowed" are usually 20-50%?

GENIE Model Uncertainty	GENIE Knob	Description	$\pm 1\ \sigma$
M_A (Elastic Scattering)	MaNCEL	Adjust M_A in elastic scattering cross section	$\pm$ 25%
M_A (CCQE Scattering)	MaCCQE	Adjust M_A in Llewellyn-Smith cross section, affecting shape and normalization	$\pm$ 25%
CCQE Normalization	NormCCQE	Adjusts CCQE Normalization	$\pm$ 25%
CCQE Vector Form factor model	VecFFCCQEshape	Changes BBBA to dipole, affecting shape only	$\pm$ 25%
CC Resonance Normalization	NormCCRES	Changes the normalization of CC Rein-Sehgal cross section	$\pm$20%
NC Resonance Normalization	NormNCRES	Changes the normalization of NC Rein-Sehgal cross section	$\pm$20%
M_A (Resonance Production)	MaRES	Adjusts M_A in Rein-Sehgal cross section, affecting shape and normalization	$\pm$20%
M_V (Resonance Production)	MvRES	Adjusts M_V in Rein-Sehgal cross section, affecting shape and normalization	$\pm$10%
1 π production from $\frac{\nu p}{\bar{\nu} n}$ non resonant interactions	Rvp1pi	Affects NC and CC production of single pion final states from non resonant inelastic scattering with νp,$\bar{\nu} n$ initial states	$\pm$50%

GENIE Model Uncertainty	GENIE Knob	Description	1 σ
1 π production from $\frac{\nu n}{\bar{\nu} p}$ non resonant interactions	Rvn1pi	Affects NC and CC production of single pion final states from non resonant inelastic scattering with νn,$\bar{\nu} p$ inital states	$\pm$50%
2 π production from $\frac{\nu p}{\bar{\nu} n}$ non resonant interactions	Rvp2pi	Affects NC and CC production of single pion final states from non resonant inelastic scattering with νp,$\bar{\nu} n$ inital states	$\pm$50%
2 π production from $\frac{\nu n}{\bar{\nu} p}$ non resonant interactions	Rvn2pi	Affects NC and CC production of single pion final states from non resonant inelastic scattering with νn,$\bar{\nu} p$ inital states	$\pm$50%
Bodek-Yang parameter A_{HT}	AhtBY	Refines Bodek-Yang model parameter A_{ht} (shape and normalization effect)	$\pm$25%
Bodek-Yang parameter B_{HT}	BhtBY	Refines Bodek-Yang model parameter B_{ht} (shape and normalization effect)	$\pm$25%
Bodek-Yang parameter C_{V1u}	CV1uBY	Refines Bodek-Yang model parameter CV1u (shape and normalization effect)	$\pm$30%
Bodek-Yang parameter C_{V2u}	CV2uBY	Refines Bodek-Yang model parameter CV2u (shape and normalization effect)	$\pm$40%
DIS CC Normalization	NormDISCC	Adjusts overall normalization of the non-resonance inclusive cross section	

GENIE Systematic Uncertainties used in MINERvA for FSI Uncertainties

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- But you can find this list in some form in most MINERvA theses
- So how can we hope to make precision measurements when the variations that are "allowed" are usually 20-50%?

FSI Uncertainty	GENIE Knob	Description	1 σ
Pion mean free path	MFP_pi	Adjusts mean free path for pions	$\pm 20\%$
Nucleon mean free path	MFP_N	Adjusts mean free path for nucleons	$\pm 20\%$
Pion - absorption	FrAbs_Pi	Adjusts absorption probability for pions, for given total rescattering probability	$\pm 30\%$
Pion - charge exchange	FrCEx_Pi	Adjusts charge exchange probability for pions, for given total rescattering probability	$\pm 50\%$
Pion - elastic	FrElas_Pi	Adjusts elastic probability for pions, for given total rescattering probability	$\pm 10\%$
Pion - inelastic	FrInel_Pi	Adjusts inelastic probability for pions, for given total rescattering probability	$\pm 40\%$
Pion - pion production	FrPiProd_Pi	Adjusts pion production probability for pions, for given total rescattering probability	$\pm 20\%$
Nucleon - charge exchange	FrICEx_NN	Adjusts charge exchange for nucleons, for given total rescattering probability	$\pm 50\%$
Nucleon - elastic	FrElas_N	Adjusts elastic probability for nucleons, for given total rescattering probability	$\pm 30\%$
Nucleon - inelastic	FrInel_N	Adjusts inelastic probability for nucleons, for given total rescattering probability	$\pm 40\%$
Nucleon - absorption	FrAbs_N	Adjusts absorption probability for nucleons, for given total rescattering probability	$\pm 20\%$
Nucleon - pion production	FrPiProd_N	Adjusts pion production probability for nucleons, for given total rescattering probability	$\pm 20\%$

FSI Uncertainty	GENIE Knob	Description	1 σ
AGKY hadronization model for x_F distribution	AGKYxF1pi	Adjusts x_F distribution for low multiplicity N + pi DIS fs, produced by AGKY	$\pm 20\%$
AGKY hadronization model for p_T model	AGKYpT1pi	Adjusts p_T distribution for low multiplicity N + pi DIS fs, produced by AGKY	$\pm 3\%$
Delta decay angular distribution	Theta_Delta2Npi	Changes delta decay angular distribution	On/off

Comparison from Jeremy's talk yesterday: MINERvA has 32 GENIE knobs (plus knobs from MINERvA data sideband discrepancies)
NOvA has ~70 knobs,
T2K has ~100 knobs

“Inherited” vs “Bespoke” Uncertainties

- MINERvA’s base tune gets modified by a few other data sets where we can, uncertainties come from those measurements/estimates
- • Valencia RPA Reweight J. Nieves, Jose Enrique Amaro, and M. Valverde. In: Phys. Rev. C70 (2004)
- • Low Recoil 2p2h Reweight from MINERvA’s Low Energy result P. A. Rodrigues, J. Demgen, E Miltenberger, et al. In: Phys. Rev. Lett. 116 (7 Feb. 2016)
- Non-Resonant pion reduction In P. Rodrigues, C. Wilkinson, and K.McFarland. In: Eur. Phys. J. C76.8 (2016), p. 474.)
- FSI Reweight
- Low Q^2 Pion Reweight P. Stowell et al. In: Physical Review D 100.7 (Oct. 2019)
- Coherent Pion Reweight A. Ramirez et al, Phys. Rev. Lett. 131, 051801 (2023)
- Diffractive Pion Reweight

Survey of MINERvA's Systematic Uncertainty Strategies

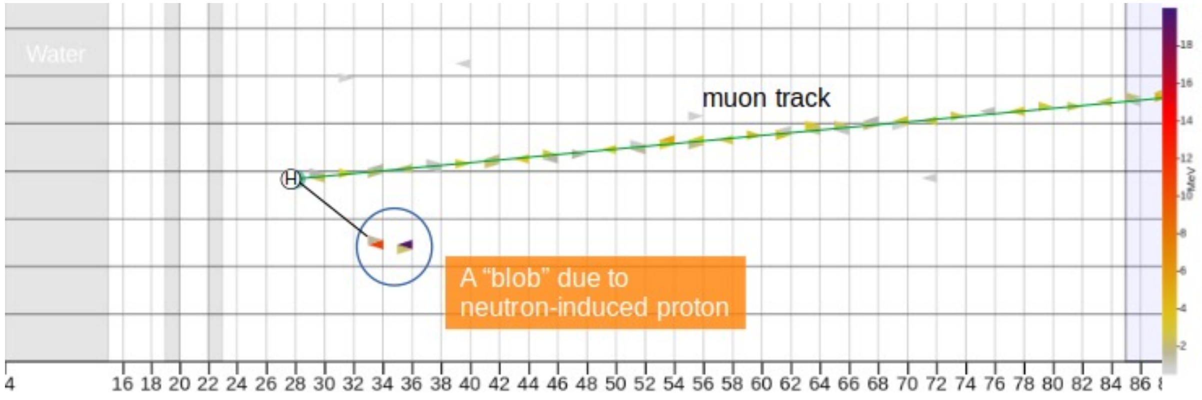
- Measuring cross section when background is high
  - When *a priori* background prediction is already pretty good
    - MINERvA's measurement of axial form factor through $\bar{\nu}_\mu p \to \mu^+ n$
  - When *a priori* background prediction is WAY OFF
    - MINERvA's measurement of ν_e& $\bar{\nu}_e$ cross sections
- Measuring cross section when background is low, but signal prediction is WAY off
  - MINERvA's measurement of pions down to 0 Kinetic Energy
- Minimizing systematic uncertainties in cross section ratios
  - MINERvA's measurement of $\nu_\mu + n \to \mu^- + p$ –like vs. A

The fine art of Background Constraints: Part 1

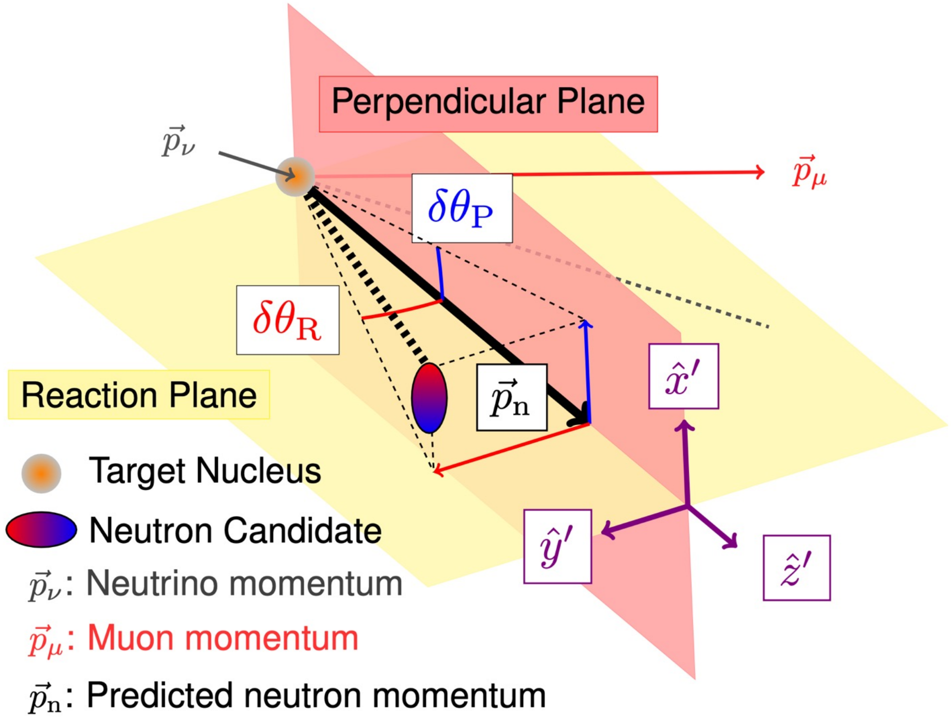
$$\bar{\nu}_\mu p \rightarrow \mu^+ n$$

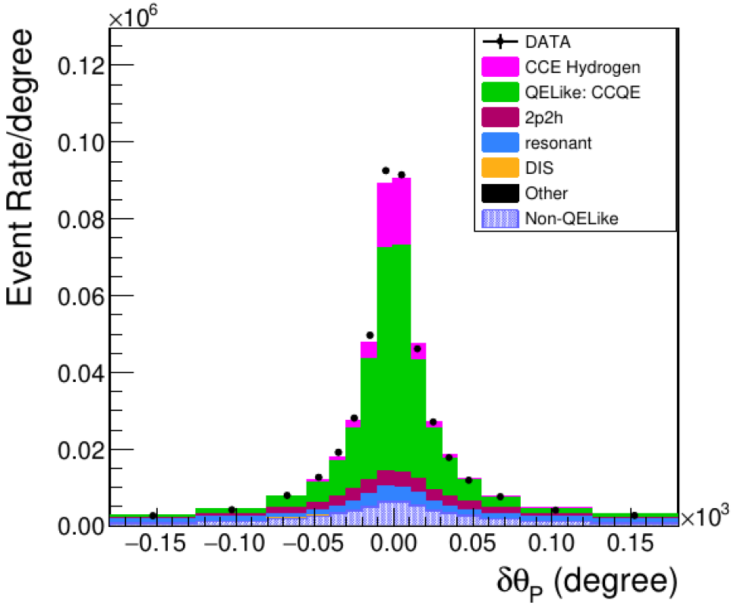
Ref: T. Cai, A. Olivier et al, Nature, 614, 48-53 (2023)

MINERvA's Axial Form Factor Measurement

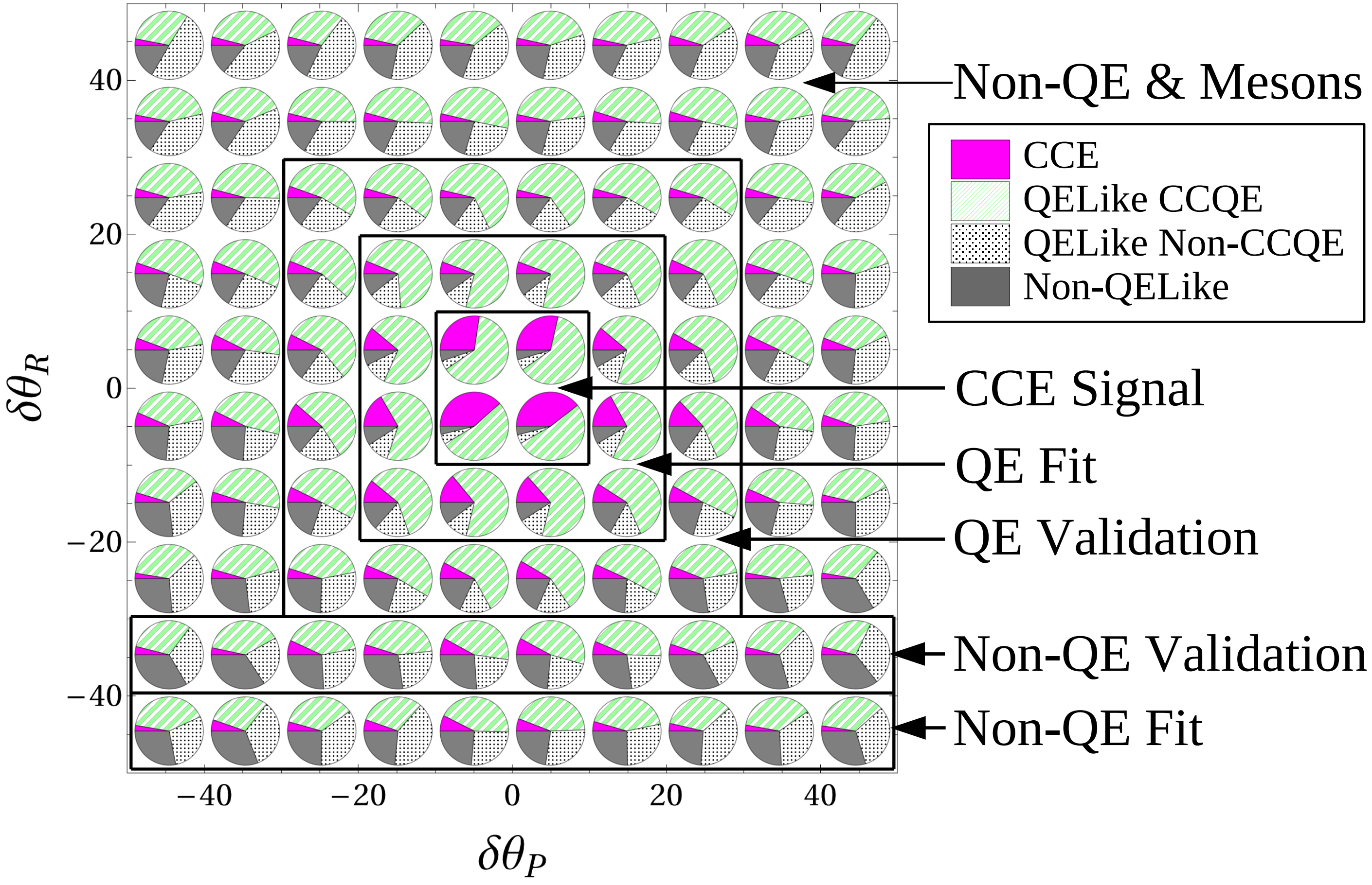


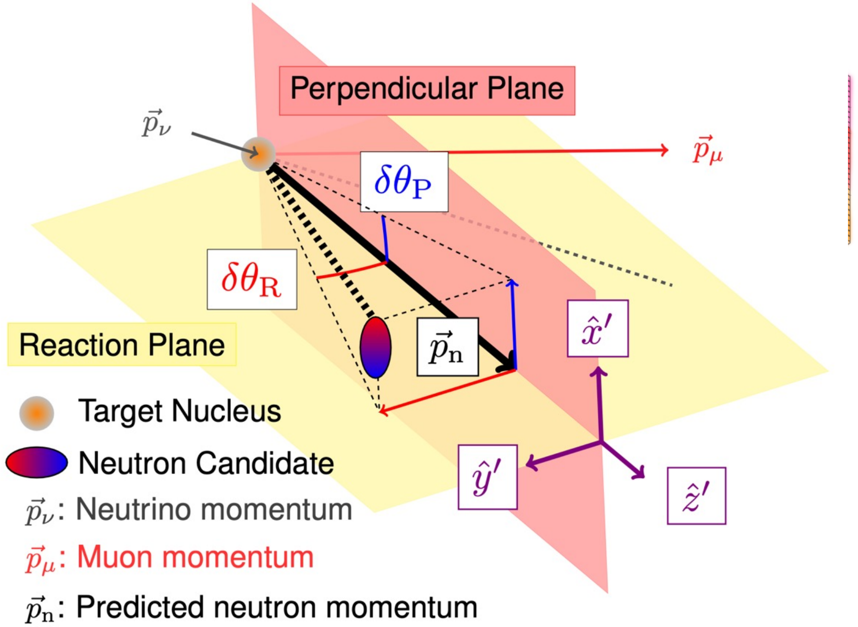
- Technique: reconstruct final state neutron direction, compare in 2 dimensions with where it would have gone in case of $\bar{\nu}_\mu p \rightarrow \mu^+ n$ scattering
- Largest backgrounds from $\bar{\nu}_\mu C \rightarrow \mu^+ n + X$ where neutron direction is additionally smeared out.
- Background systematic uncertainties from neutron interactions (see Andrew's talk on Thursday)

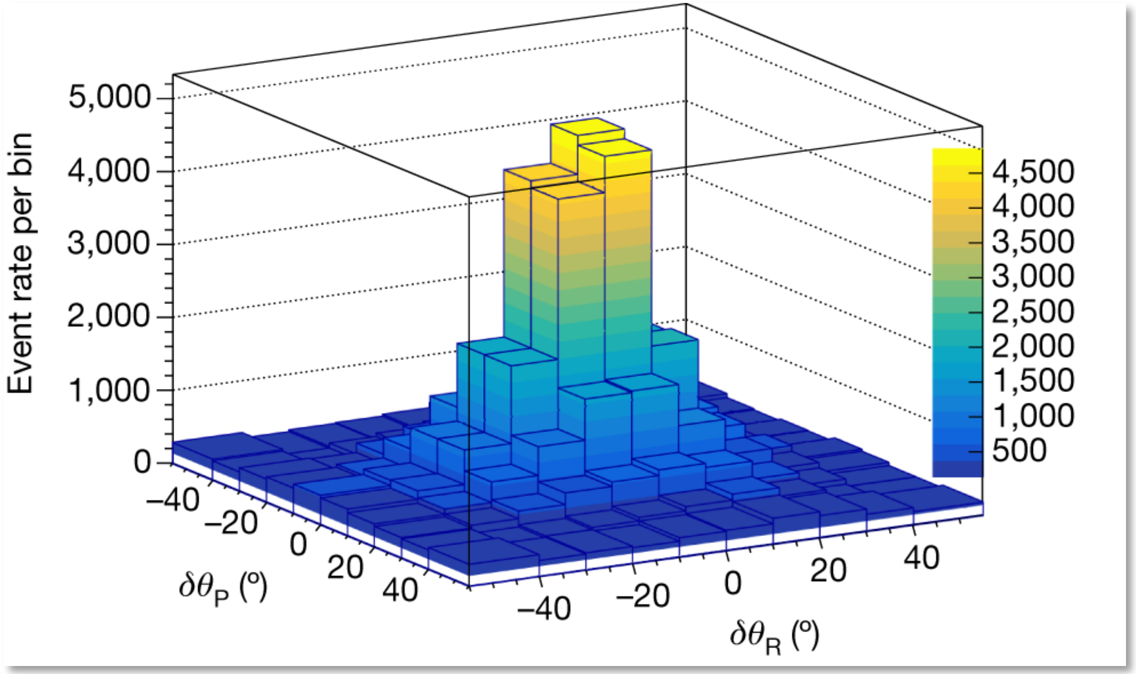




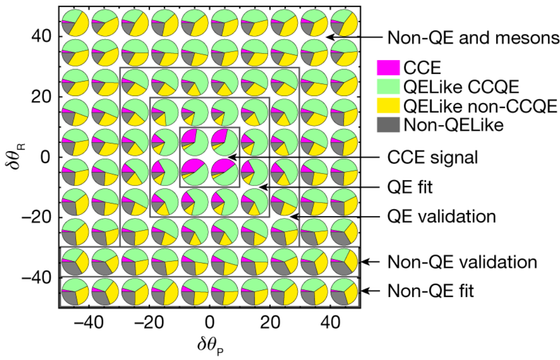
Signal, Background, and "Fit Validation" Regions

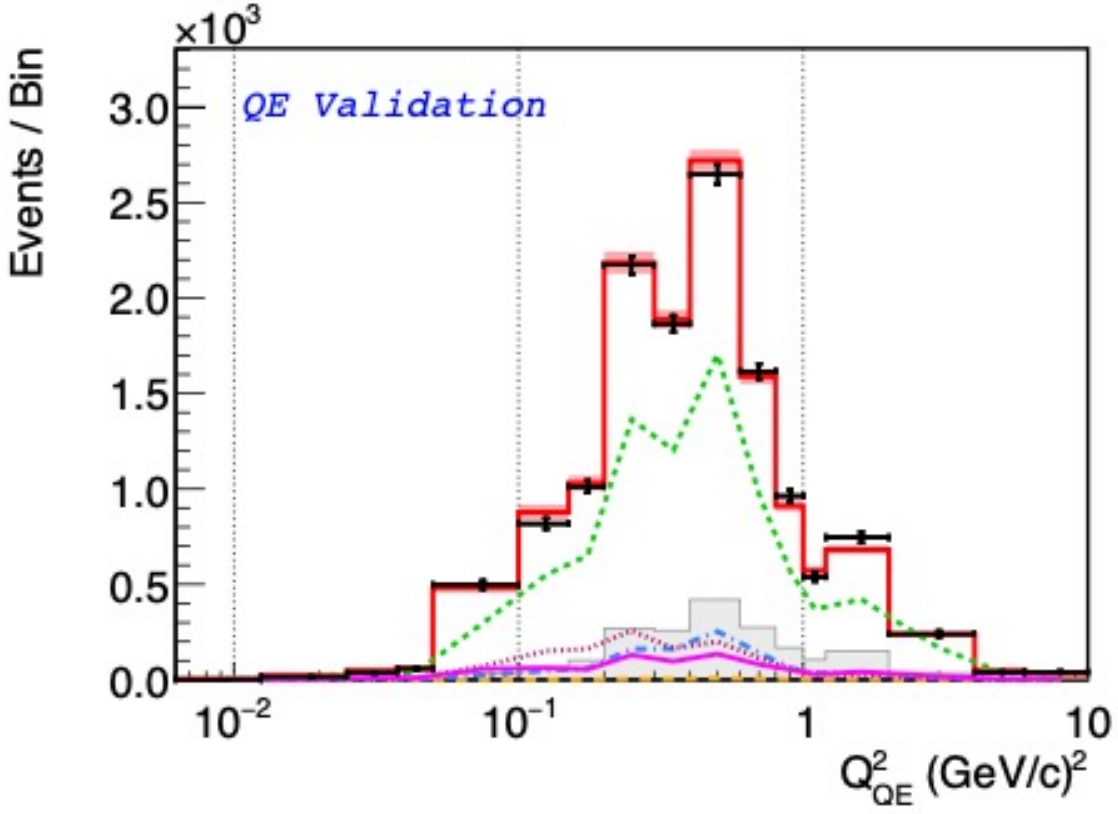


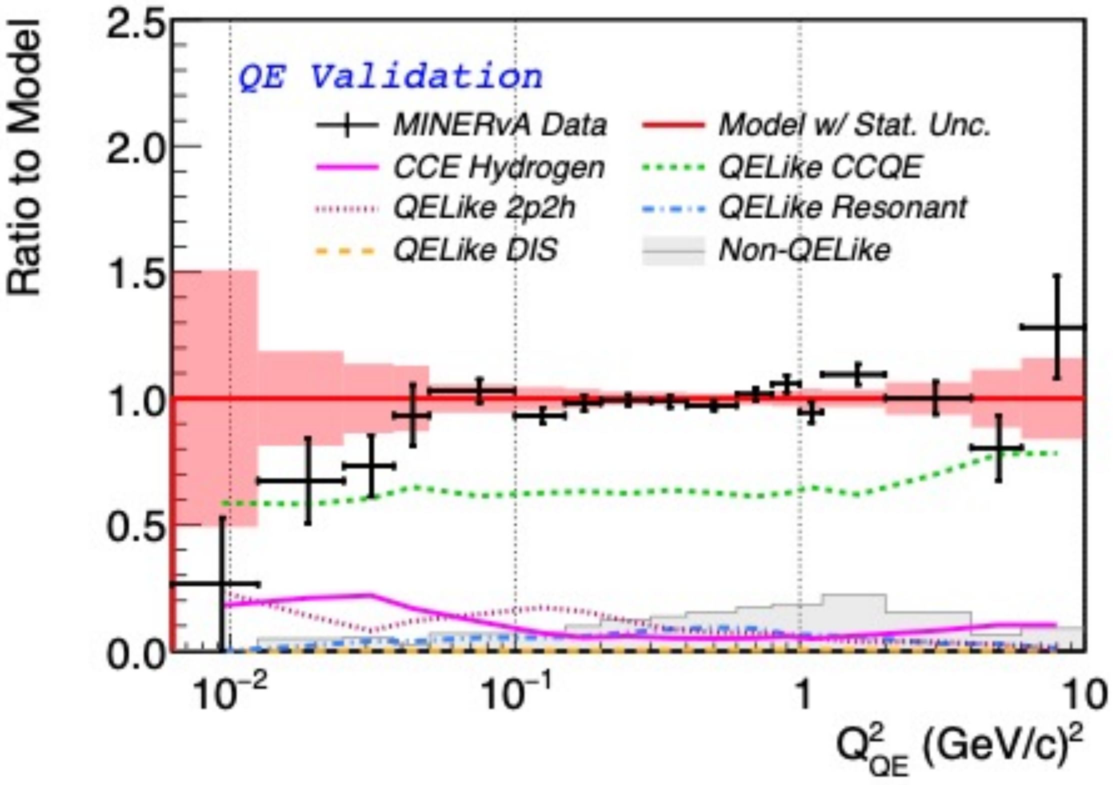




Validating the Background Prediction



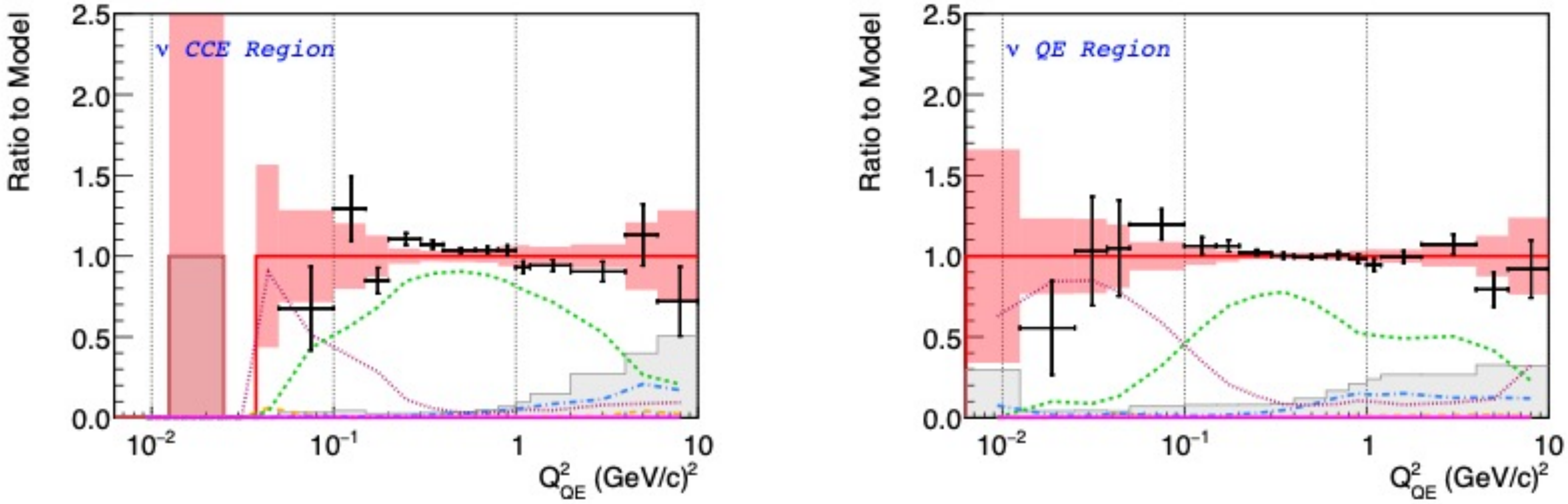




- CCQE is the dominant background. Small 2p2h, inelastic (absorbed), and Non-QELike contributions. The fitted model are well constrained by data.

NuFact23

Another test: $\nu_\mu + n \rightarrow \mu^- + p$

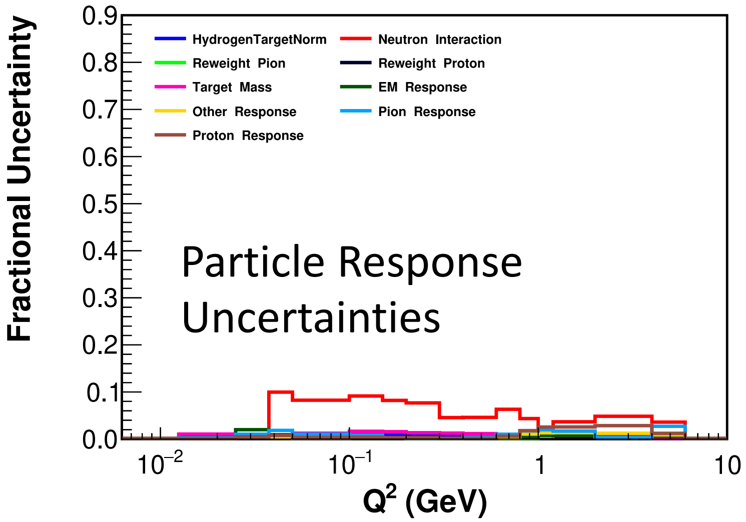


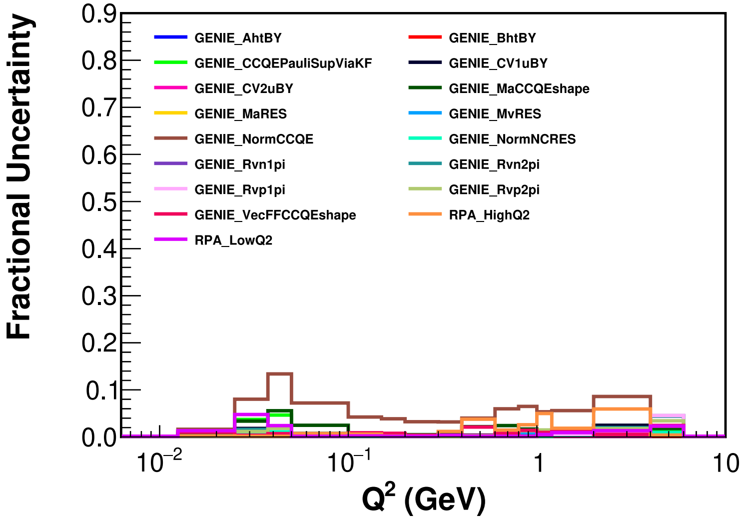
- Recipe: select events with trackable protons in a neutrino sample. Different final states and available kinematics. Apply same fitting mechanism. Data and MC mostly agree within uncertainty. Data and MC mostly agree. Disagreement can be explained by 2p2h uncertainty.

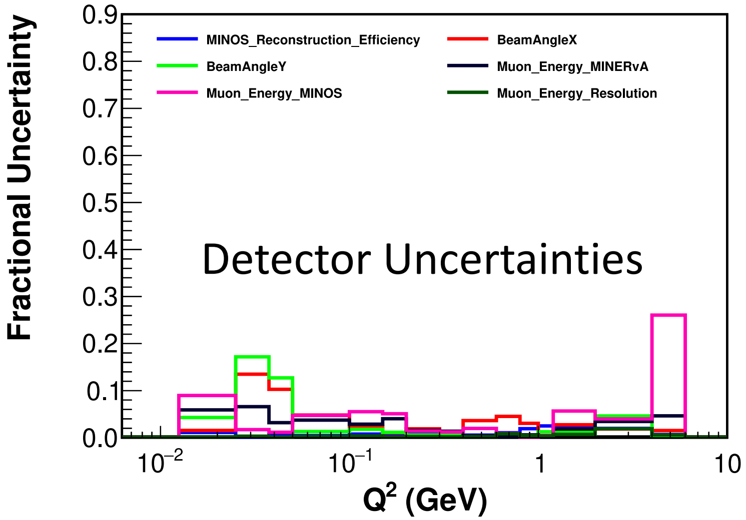
T. Cai, NuINT 2022

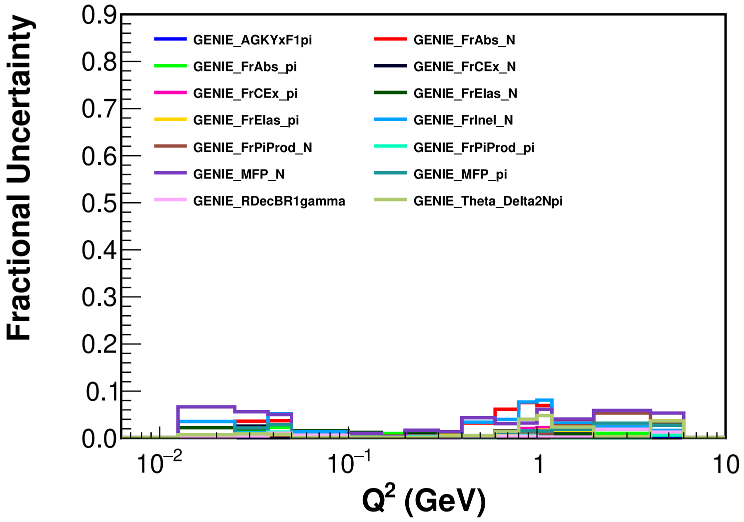
Cross Section Uncertainties

- Consider different neutrino interaction sources
- Add extra “2p2h” uncertainty where we vary that contribution by xx% based on our earlier Low energy measurements
- Have to show uncertainties on log scale to see all of them including statistics



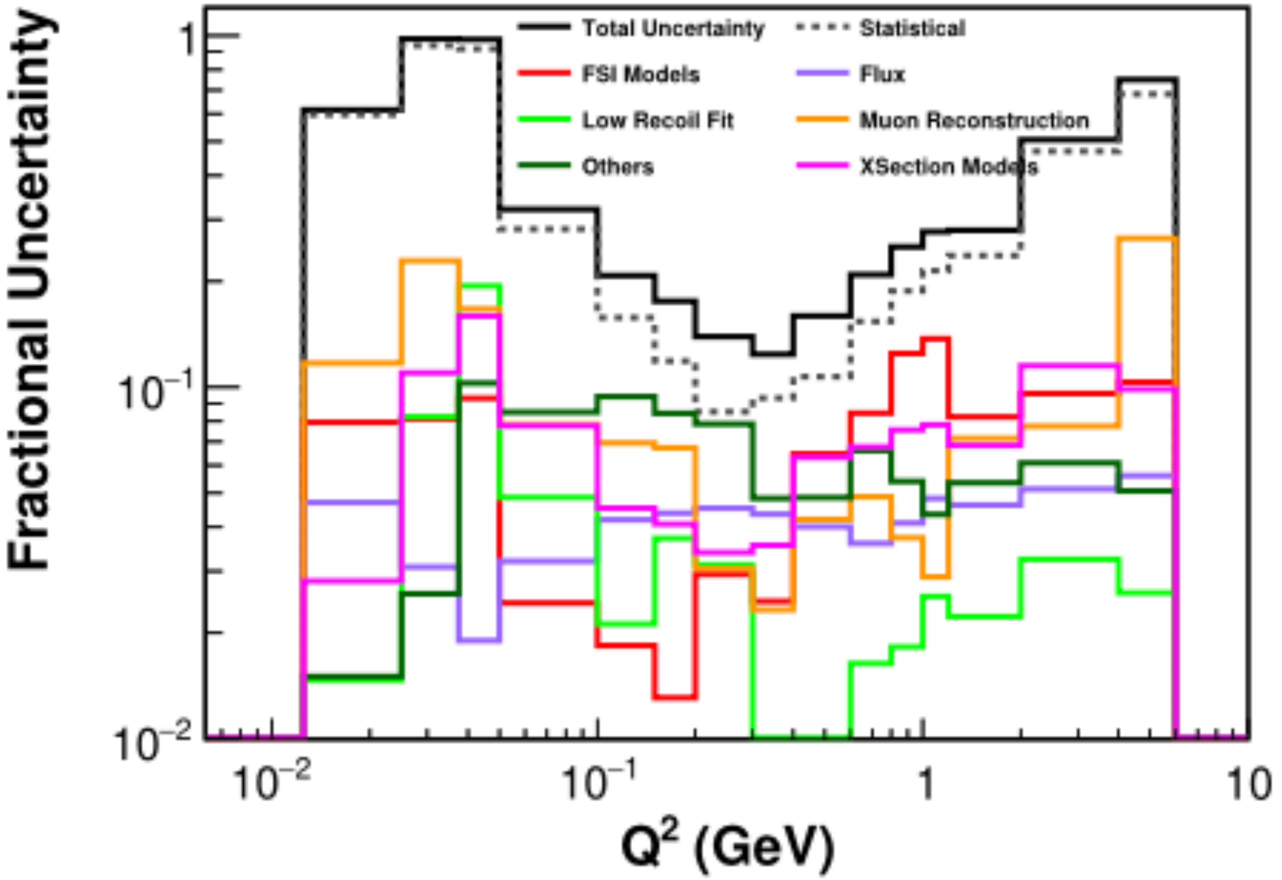






T. Cai, NuINT 2022

Uncertainties in the Axial Form Factor Cross-Sections



Dominated by statistical uncertainty after the background subtraction.

Systematic uncertainties from residuals of background subtraction

Particle responses in the "other" category, dominated by neutron systematics.

T. Cai, NuINT 2022

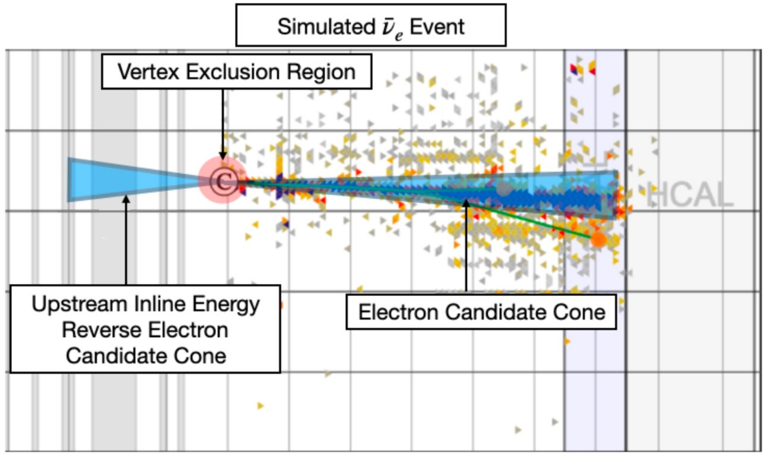
The fine art of Background Constraints: Part 2

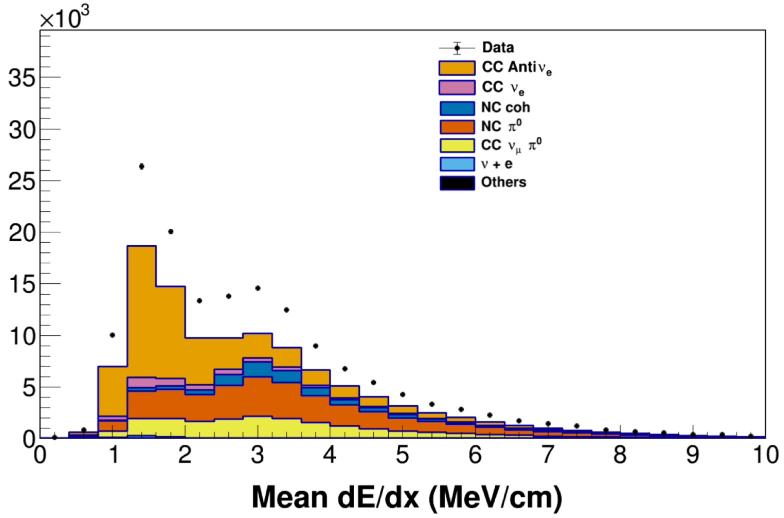
$\bar{\nu}_e CH \rightarrow e^+ X$ and $\nu_e CH \rightarrow e^- X$ at low recoil

Ref: S. Henry, H. Su et al, Phys. Rev. D 109, (2023) 092008

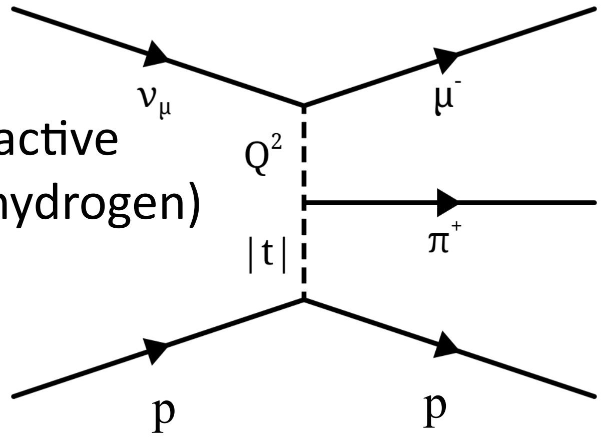
ν_e & $\bar{\nu}_e$ Cross Sections at low recoil

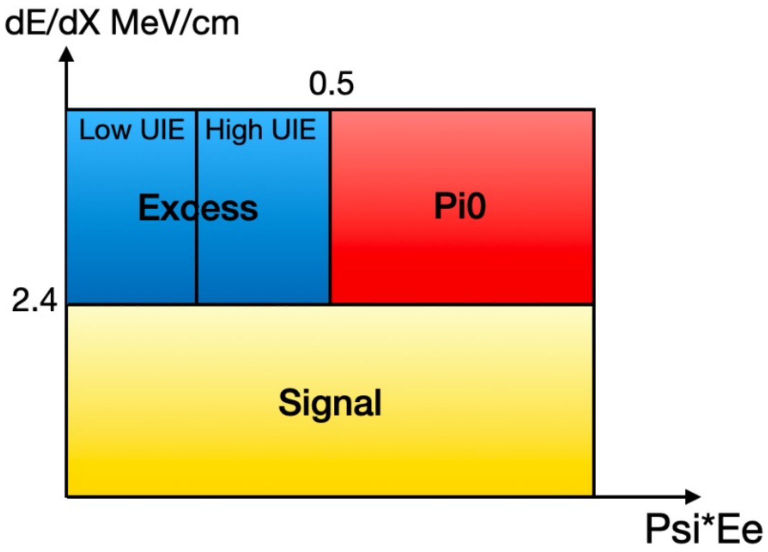
- Main backgrounds: $NC\pi^0$ (inelastic, coherent, diffractive)
- Background predictions were very wrong because of missing diffractive π^0, and not enough coherent π^0 at high energies.
- How to deal with this?





Diffractive (on hydrogen)





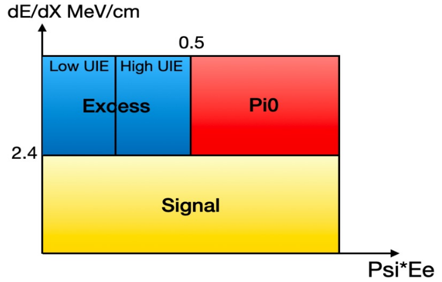
Divide high dE/dx region into diffractive-like (recoiling proton at vertex), coherent-like, and incoherent-like to characterize backgrounds.
Psi=E(outside cone)/E(inside cone)

S. Henry, H. Su et al, Phys. Rev. D 109, (2023) 092008

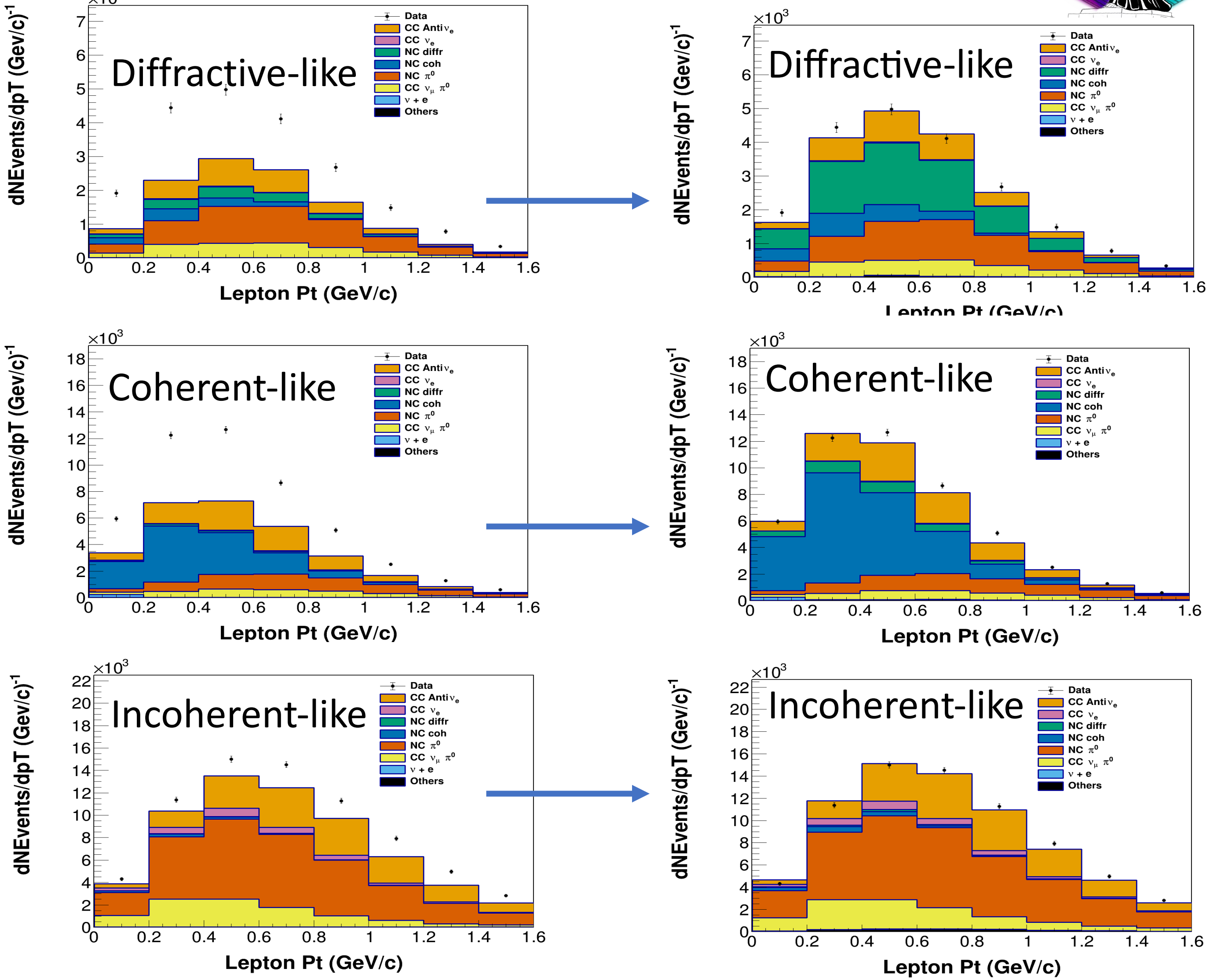
Characterization of ν_e & $\bar{\nu}_e$ Backgrounds

- Tune primarily in electron p_T for each process separately.
- "Antineutrino" beam has much less incoherent π^0 production, so use the tune in that beam for results in neutrino dominant beam
- Coherent π^0 production from carbon is dark blue--increased
- Sideband tune has tensions in FHC beam not observed in . Add an extra systematic uncertainty to cover this in FHC.

$\bar{\nu}$-mode…



Pre-Tune

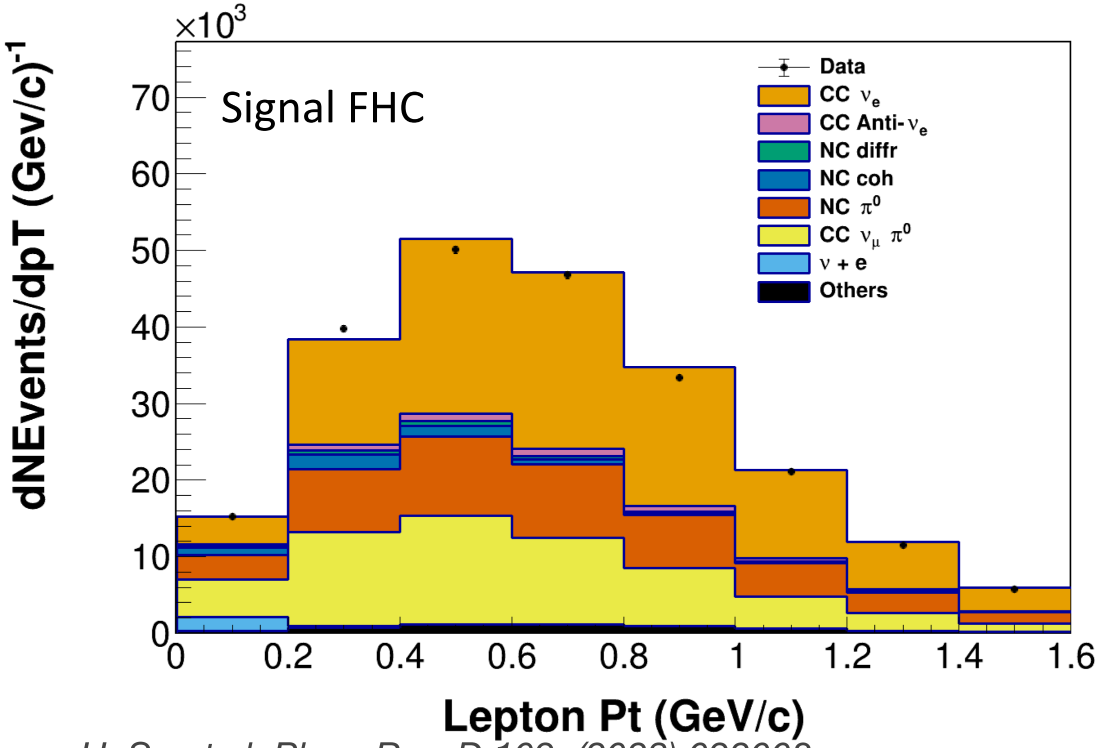


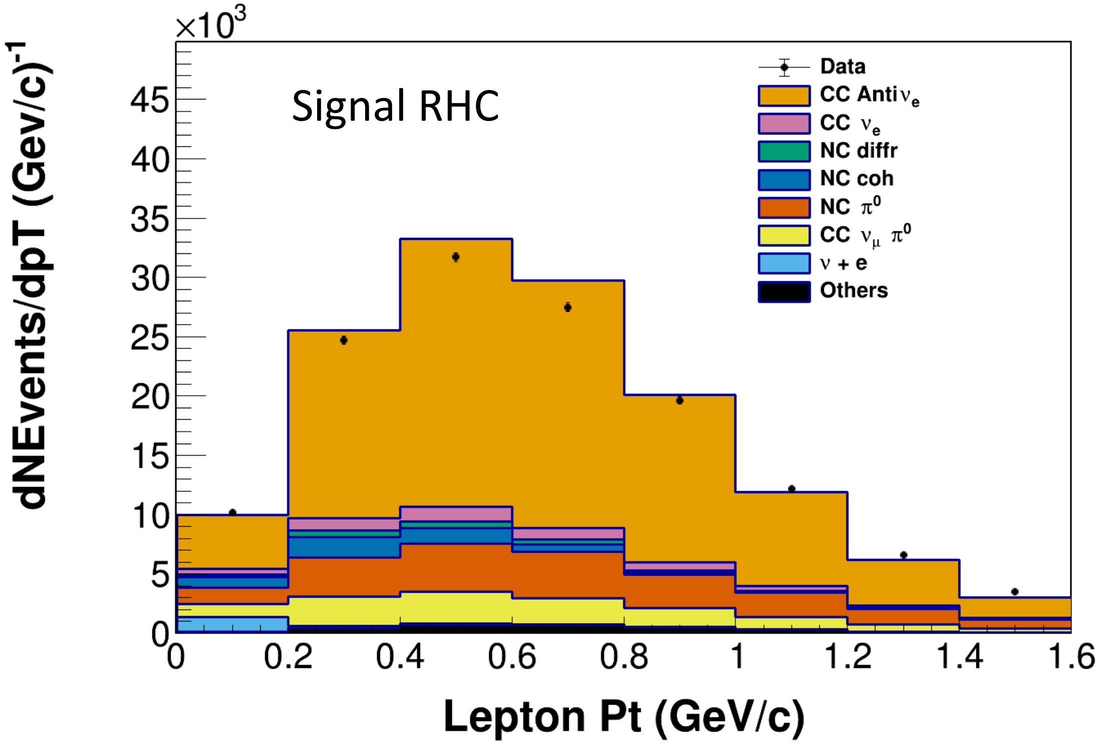
S. Henry, H. Su et al, Phys. Rev. D 109, (2023) 092008

K. McFarland, NuINT 2024

ν_e & $\bar{\nu}_e$ Signal Region after Background Tunes

- After tuning the backgrounds, compare signal region.
- As expected, backgrounds much larger in FHC (incoherent processes).
- Use FHC cross sections to predict wrong-sign background in RHC, and vice versa

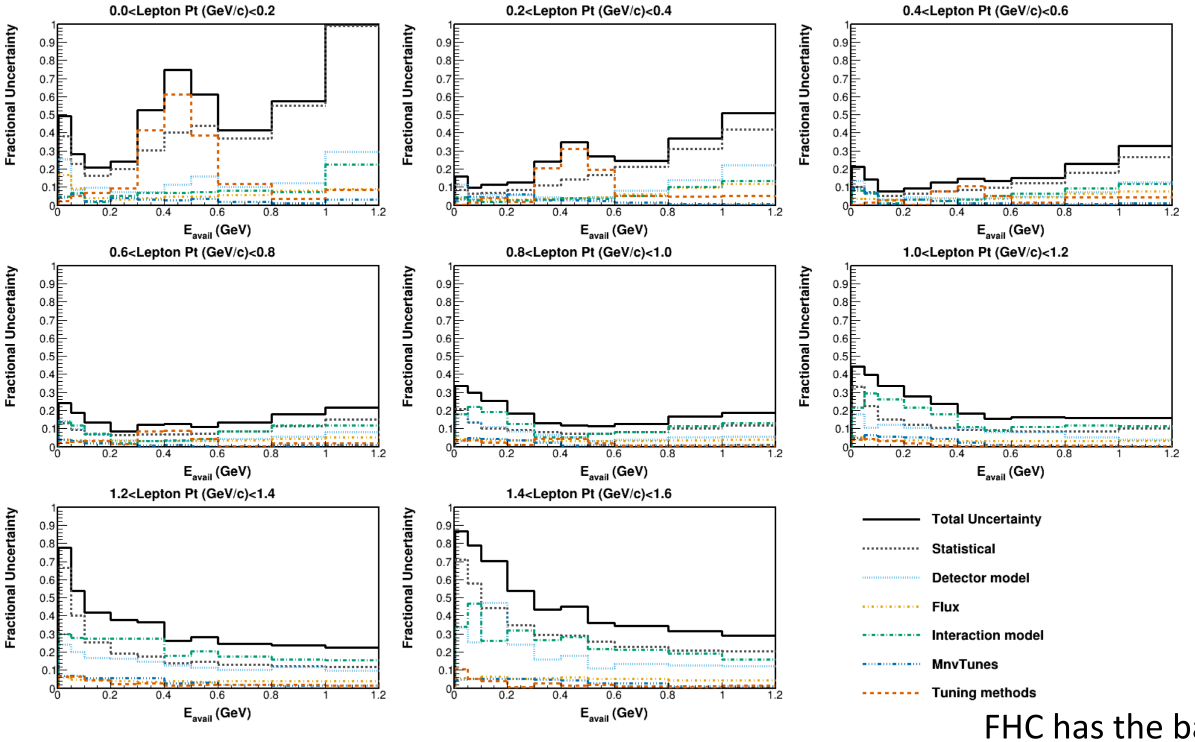




S. Henry, H. Su et al, Phys. Rev. D 109, (2023) 092008

Final Uncertainties in ν_e & $\bar{\nu}_e$ Cross Sections

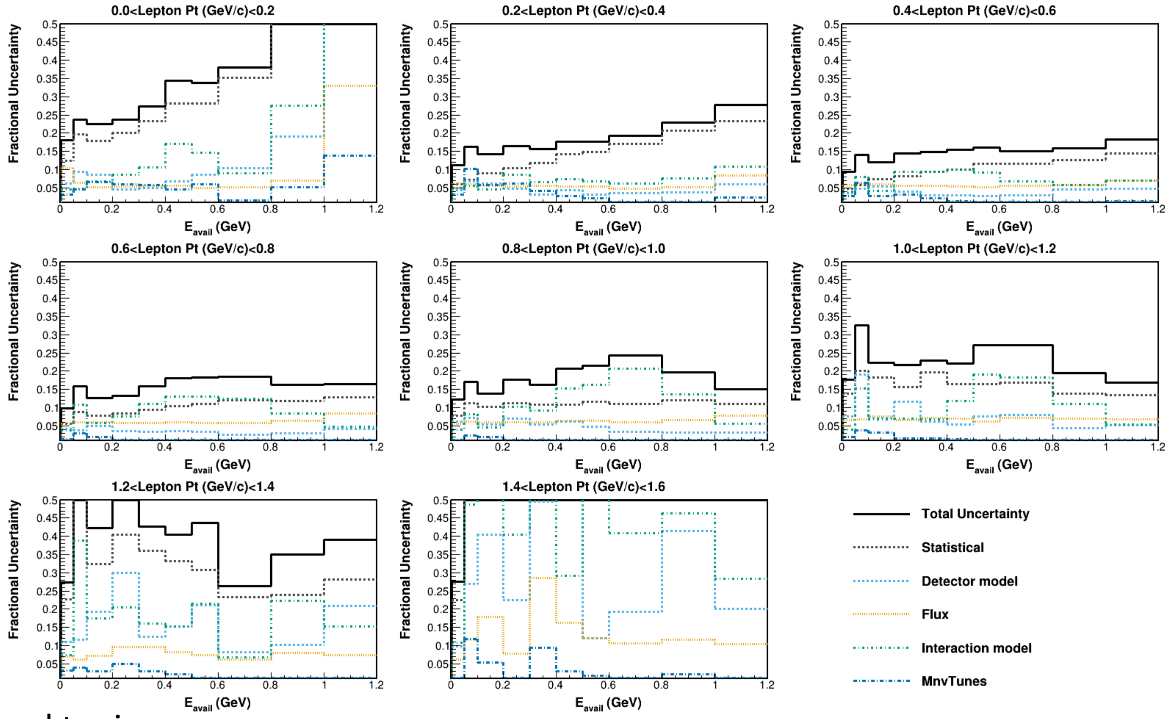
- Statistics dominated, with significant interaction model uncertainties at mid-p_T.
- Flux uncertainties ~5%.



Neutrino uncertainties

S. Henry, H. Su et al, Phys. Rev. D 109, (2023) 092008

FHC has the background tuning uncertainty, due to imperfect sidebands agreement very visible at low p_T.



Anti-neutrino uncertainties

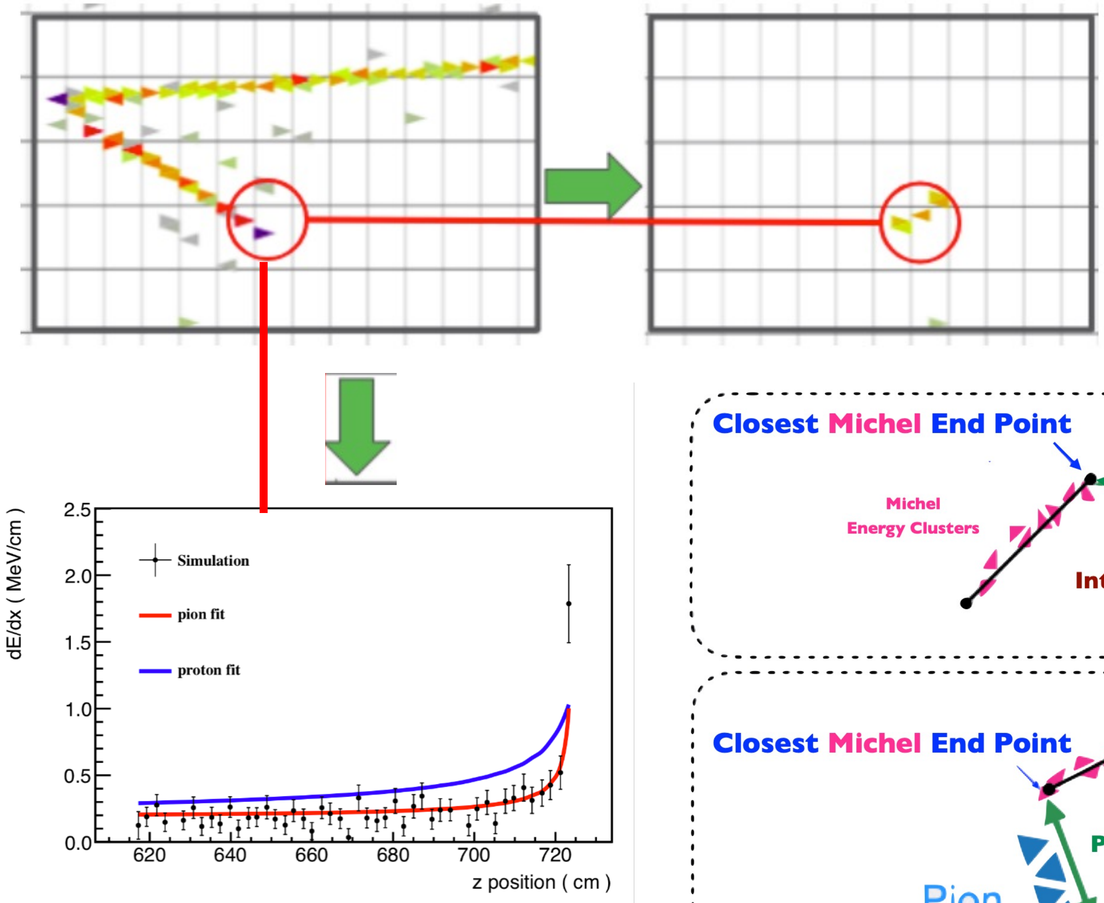
When your signal model needs work: Pion Production

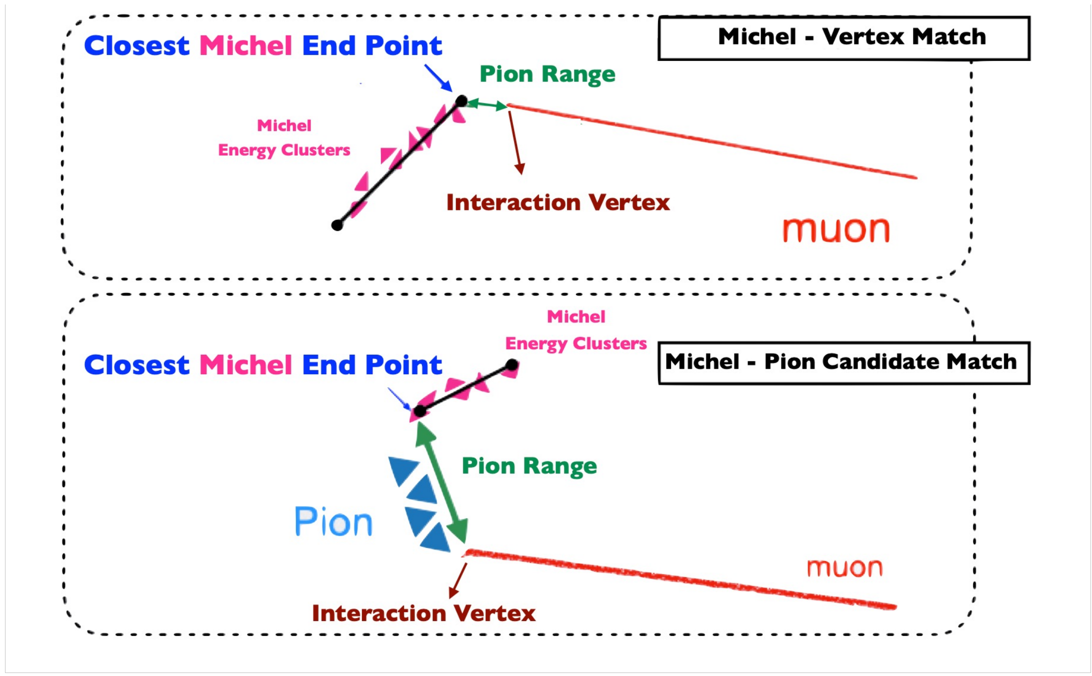
$$\nu_\mu CH \rightarrow \mu^- N\pi^+ + X$$

Ref: DH for M. Sultana, NuINT24

Pion Kinetic Energy Reconstruction, now with Michel Electron-tagged pions

- Regular pion ID: dE/dx of a track
- New: If you determine the start of the Michel Electron, AND the muon vertex , you have an observable which is a function of Kinetic Energy of pion
- No tracking needed
- This works down pion momenta of 0keV

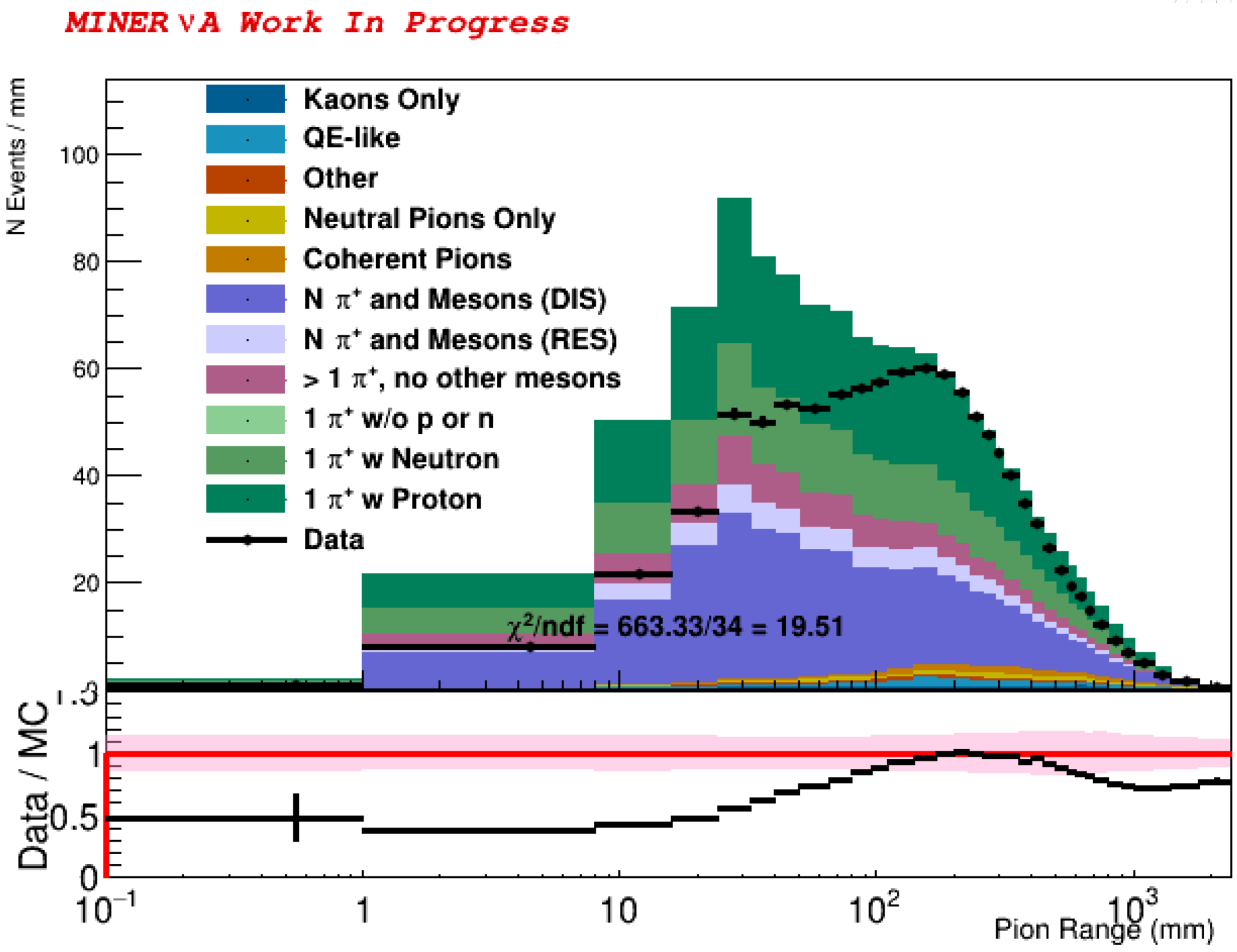




DH for M. Sultana, NuINT24

When the signal model needs work…

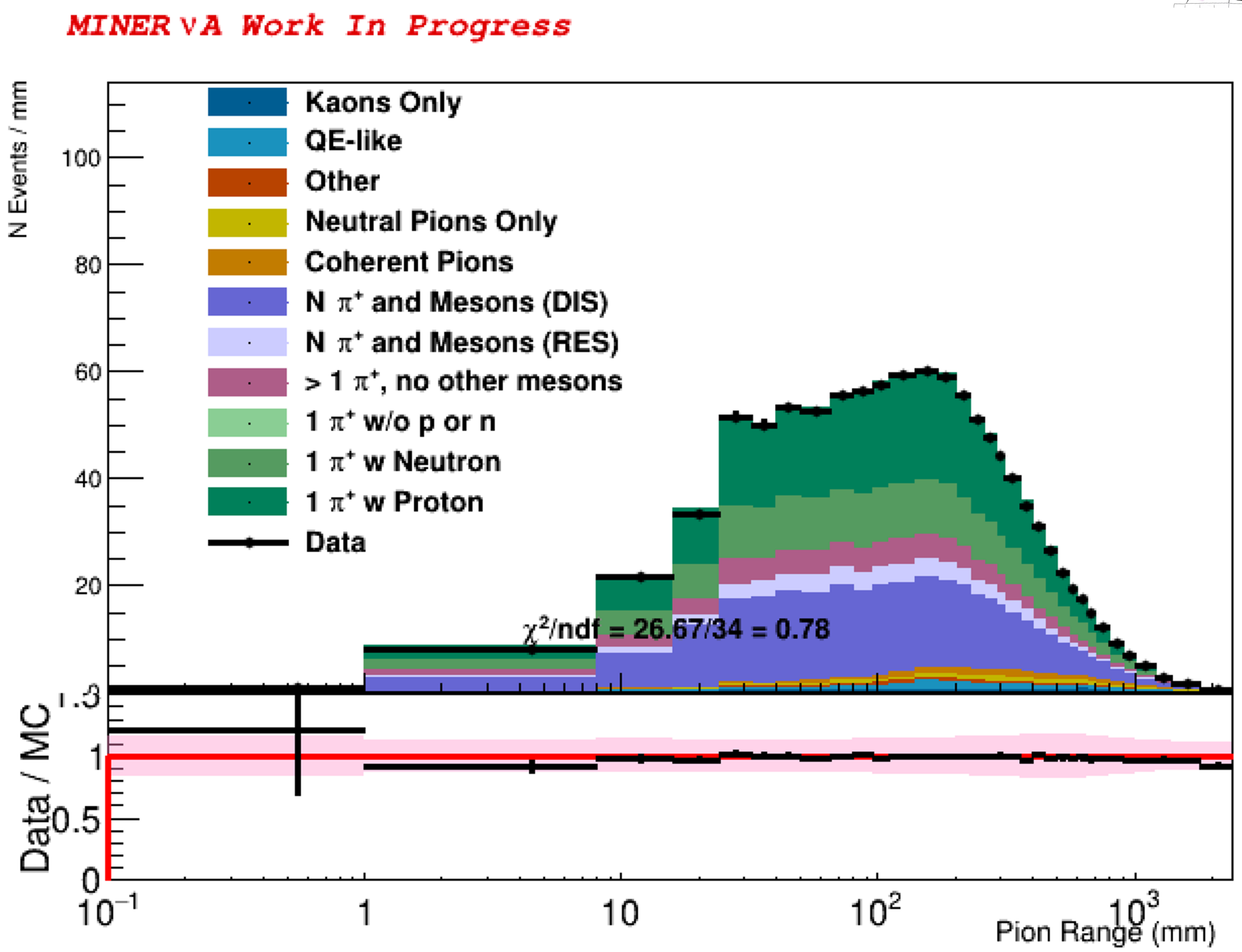
- Agreement is poor: previous models unconstrained in this kinematic region!
- This sample only has requirement of
  - negatively charged muon,
  - Muon $p_{t\mu}$<1.8GeV and 1.5GeV<p_{μ}<20GeV
  - Available energy<1.5GeV
- Prediction: MnvTunev4.3.1
- Most events ARE signal events, but a mixture of sources



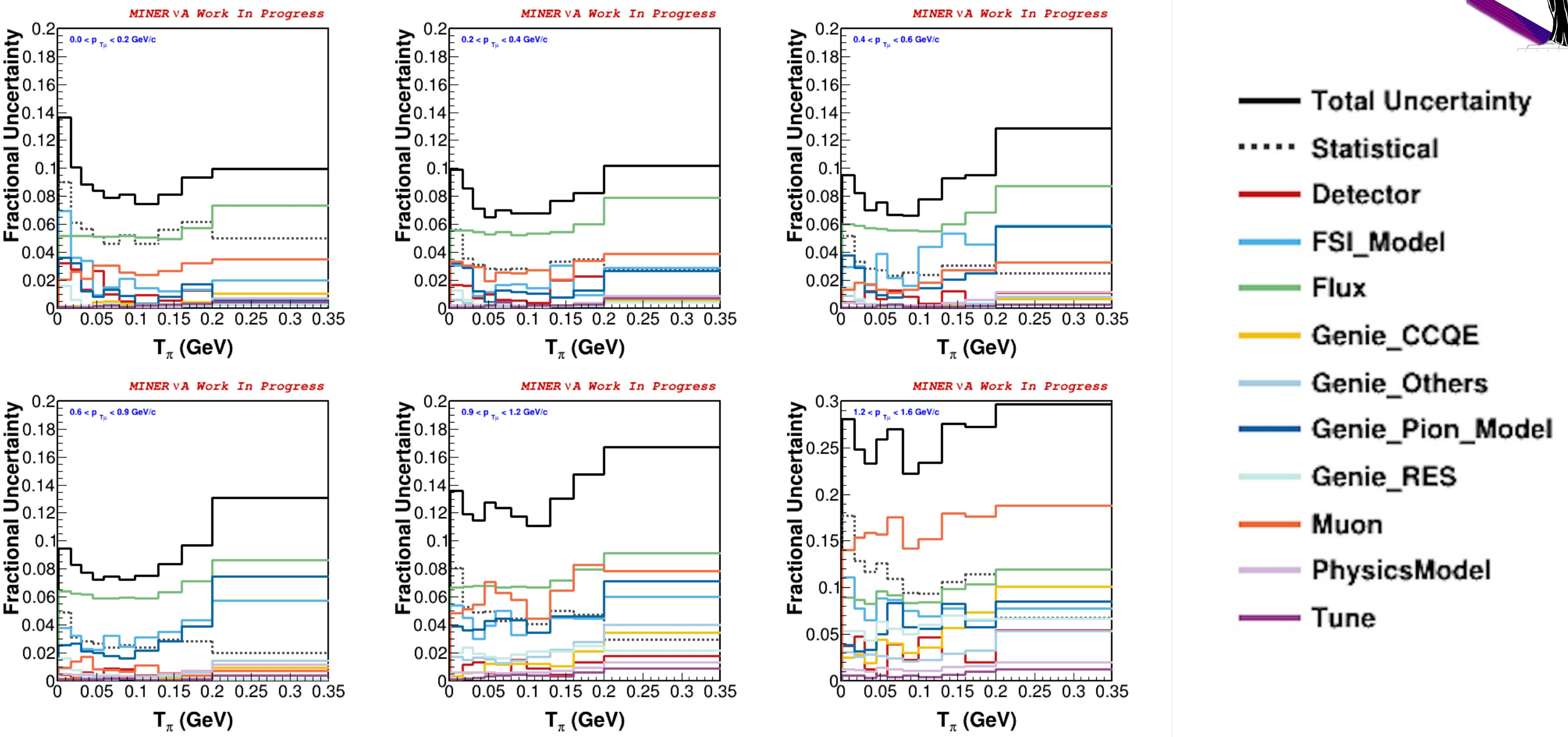
DH for M. Sultana, NuINT24

Fixing the signal model

- Have to develop a tune to weight MC to data to get more realistic smearing
- Singular Value Decomposition technique used to study migration between pion range and kinetic energy
- Backgrounds determined by sidebands in Michel e^{-}-μ vertex distance, scale factor in $p_{t\mu}$ bins, function of available energy



CC≥1π Cross Section Uncertainties versus T_π and $p_{t\mu}$



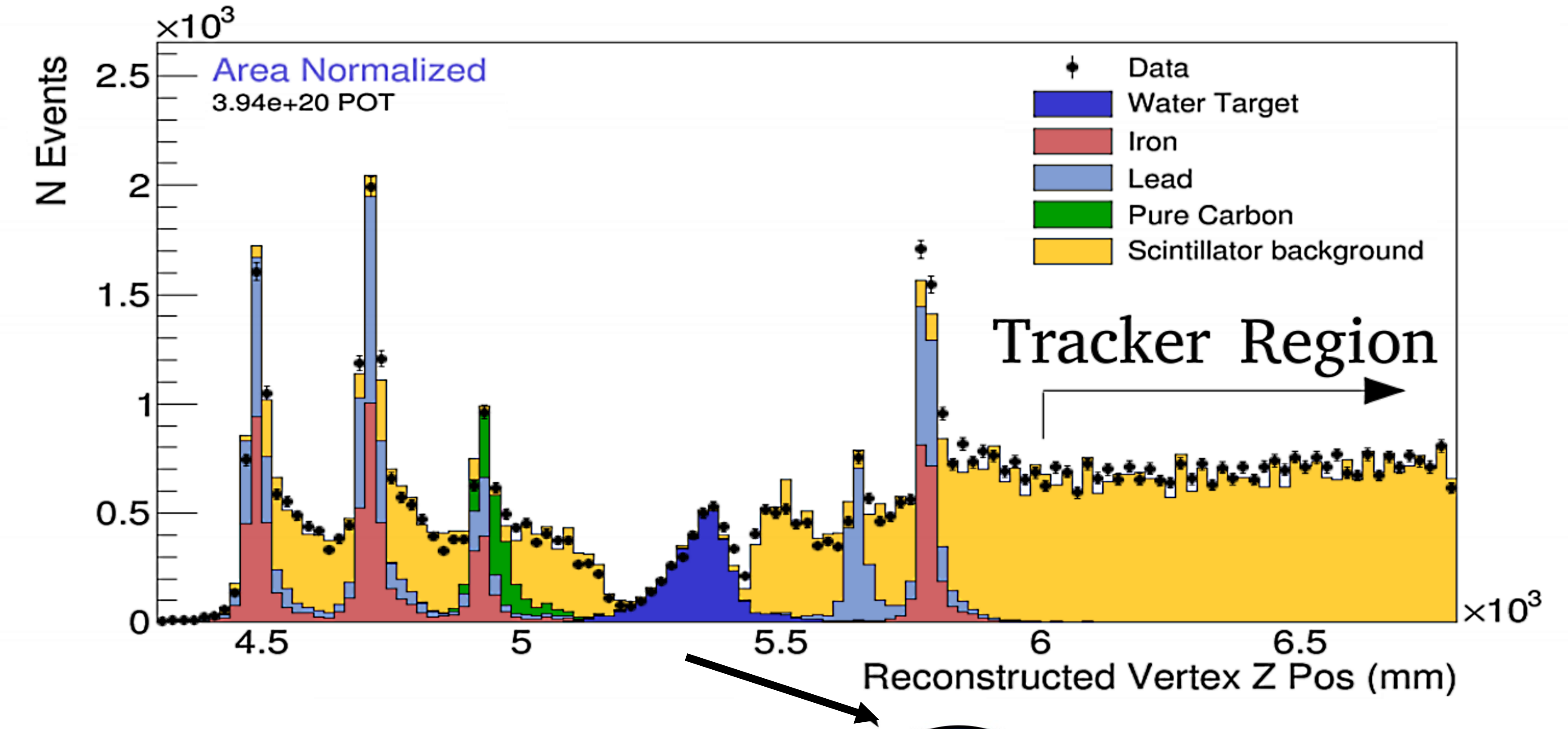
DH for M. Sultana, NuINT24

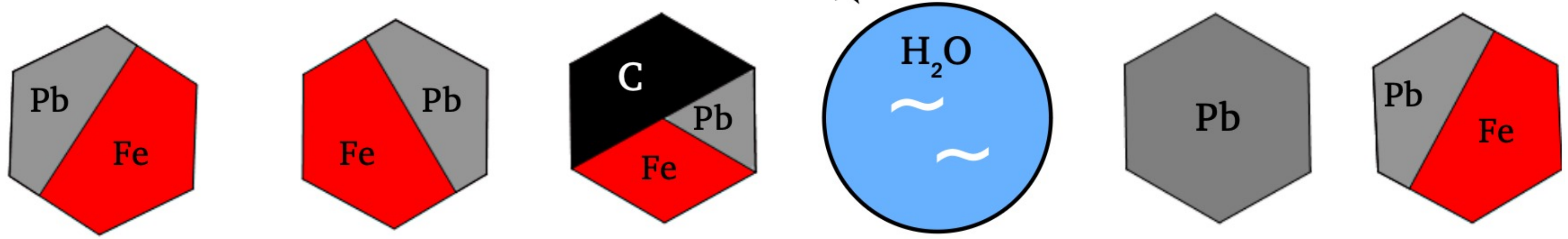
Systematic Uncertainties in Cross Section Ratios

$$\nu_\mu + C, CH, H_2O, Fe, Pb, \rightarrow \mu^- \ 0\pi^\pm + nucleons$$

Ref: J. Kleykamp JETP 3/2023, publication in progress

MINERvA's Nuclear Targets

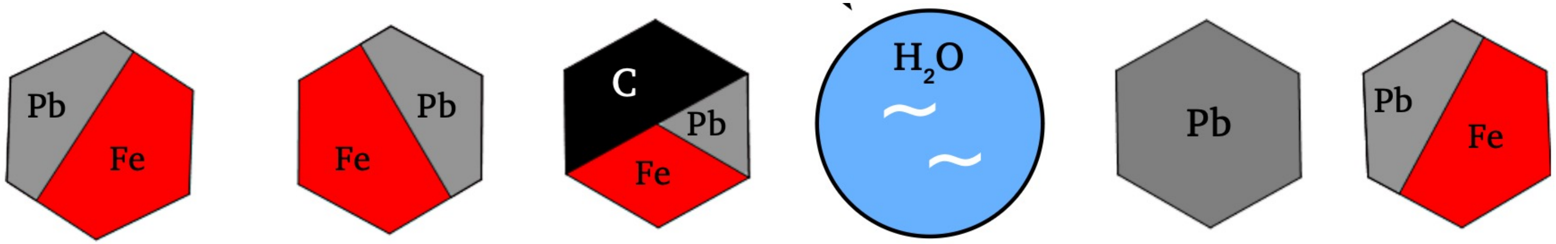


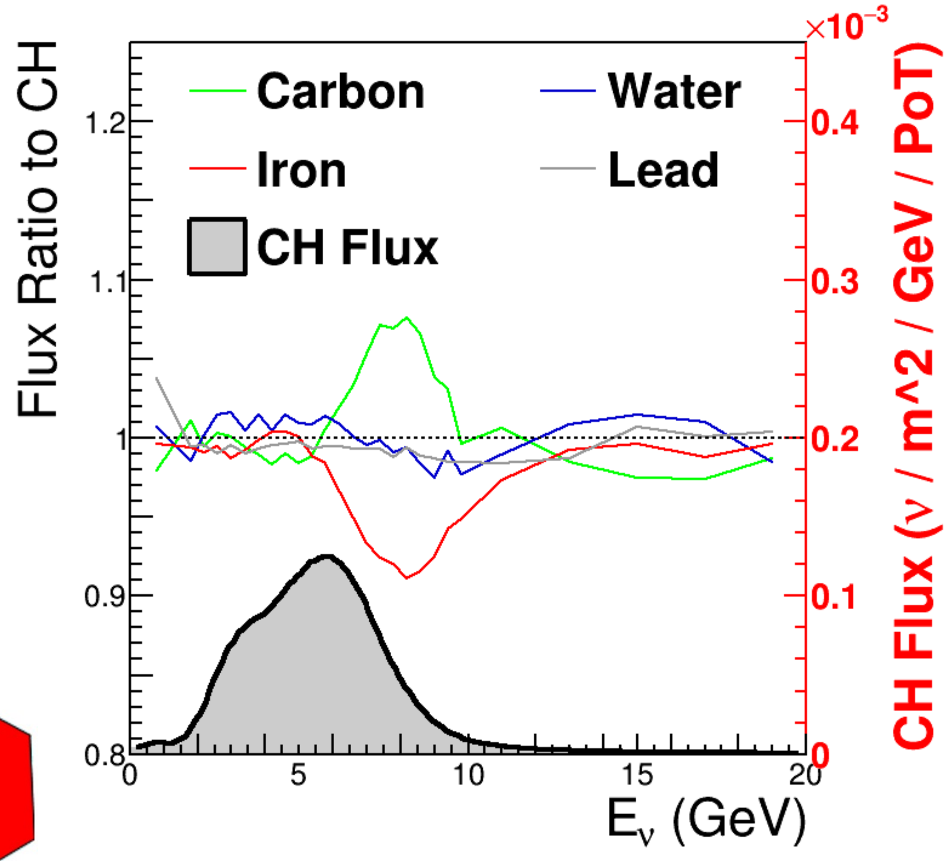


J. Kleykamp,
JETP seminar

Nuclear Target Cross Section Ratios

- Different Nuclear Targets see slightly different neutrino fluxes just by beamline and detector geometry alone
- Want to correct for this without relying on a neutrino energy estimator
- MINERvA has developed a technique to make the fluxes on different targets as similar as possible without needing to reconstruct neutrino energy: sound familiar?





"PRISM" strategy: use geometry to get around energy differences in fluxes

Nuclear Target Cross Section Ratios

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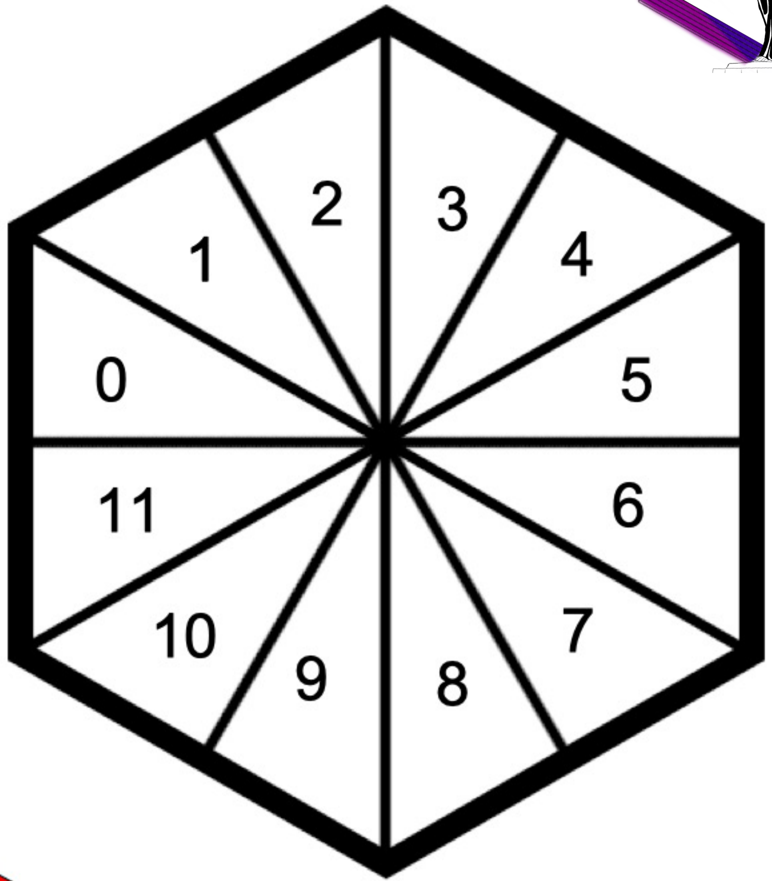
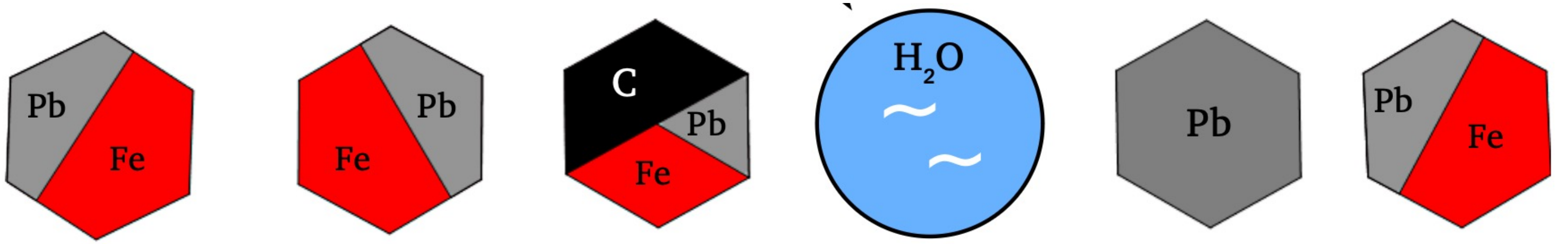
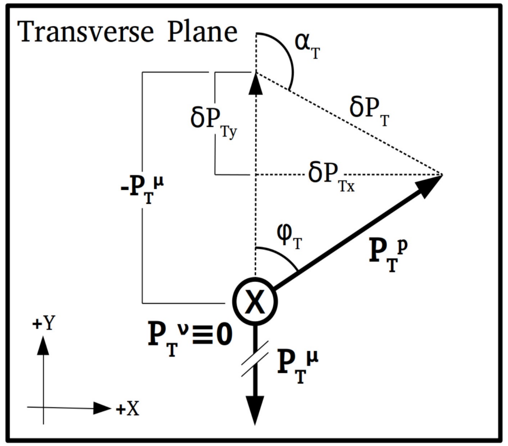




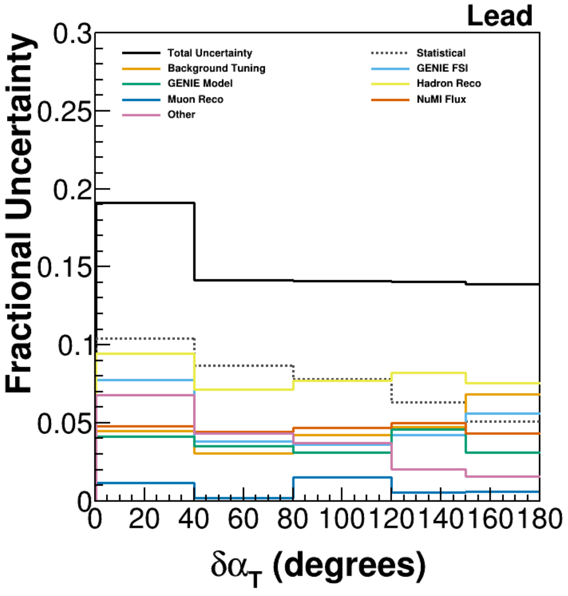
Extract CH Cross Section in 12 ”petals” and reweight to get most similar flux while using as much statistics as possible

Systematic Uncertainties on absolute Cross sections compared to A/CH ratios

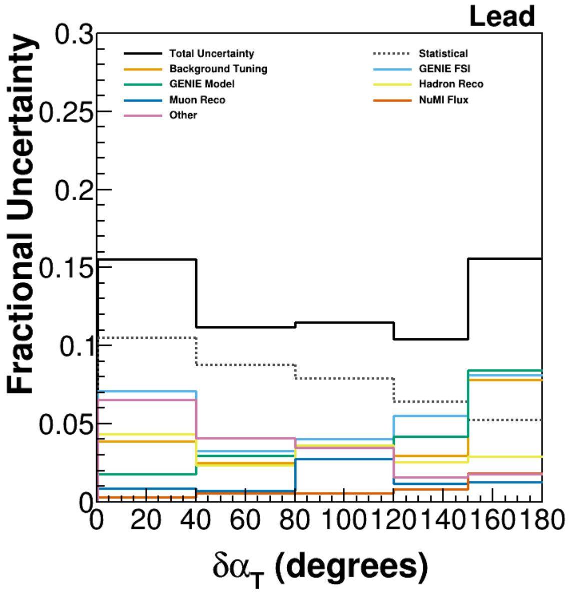
- *J. Kleykamp, draft of publication in internal review*



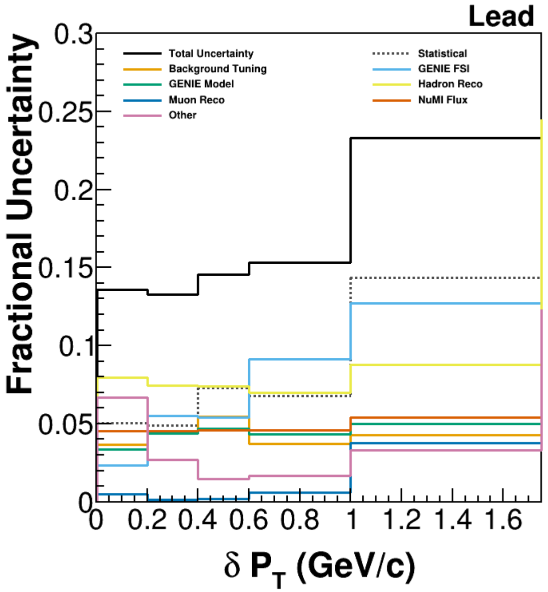
Cross Section in Pb



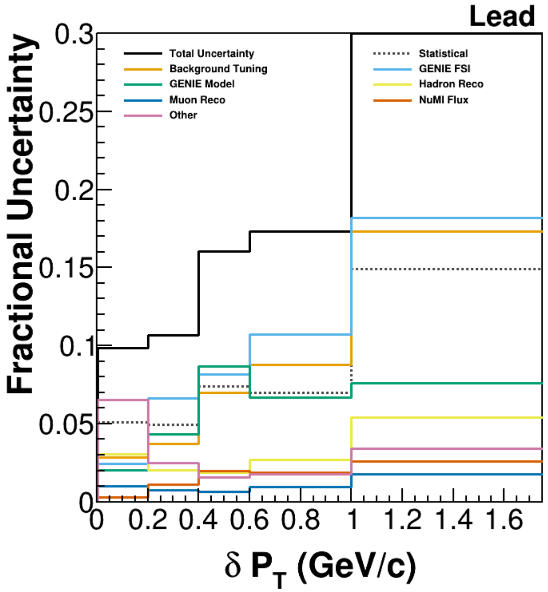
Pb/CH Cross Section Ratio



Cross Section in Pb



Pb/CH Cross Section Ratio

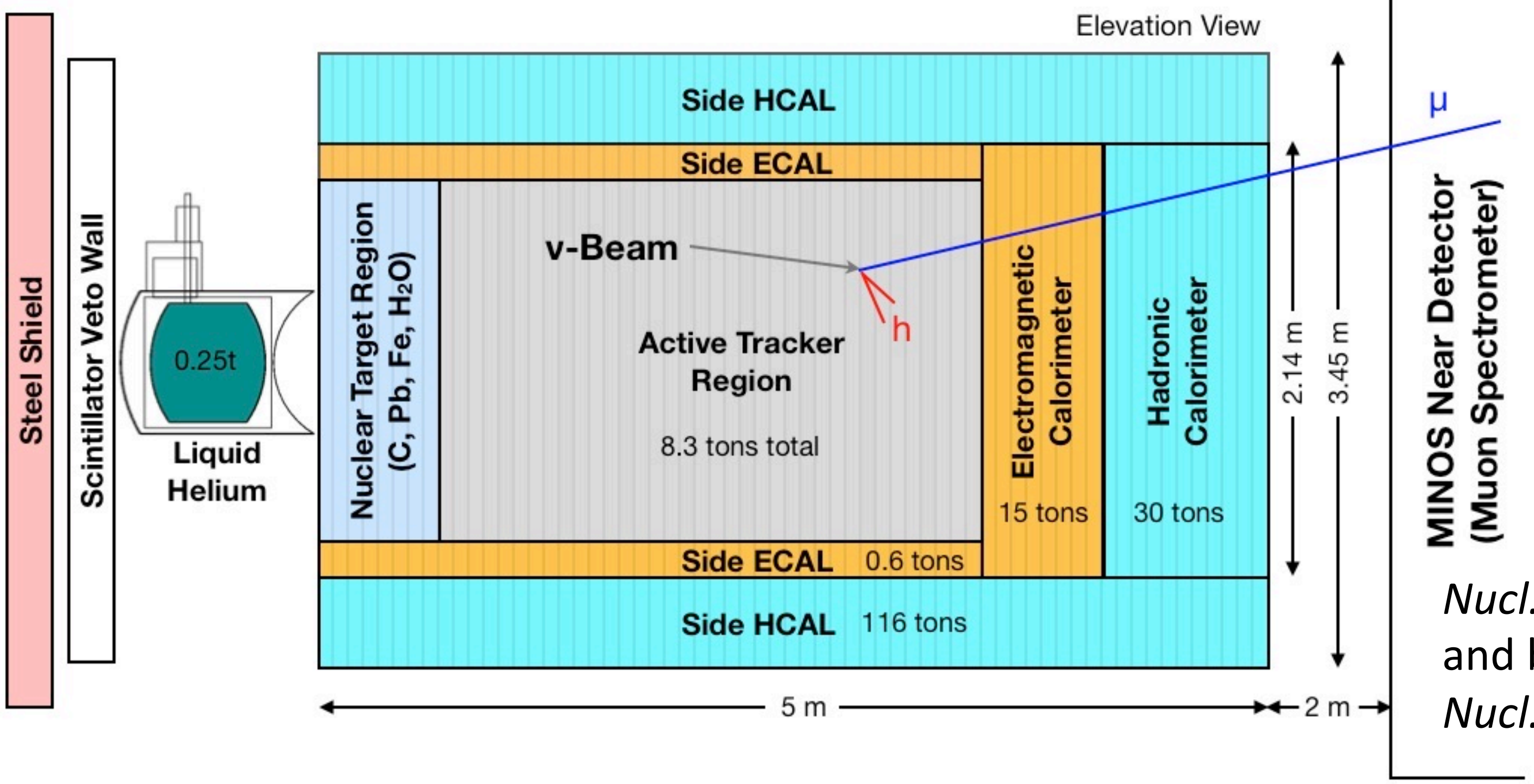


Conclusions

- MINERvA uses the data as much as possible to inform background predictions and signal model
- We also try to use other measurements: either previous MINERvA analyses or fits to bubble chamber data to improve our underlying model
- Add systematic uncertainties when there are data/simulation discrepancies in the sidebands after tuning.
- Measure cross section ratios with as similar fluxes as possible
- Resulting cross section uncertainties comparable or lower than statistical uncertainties in many MINERvA analyses

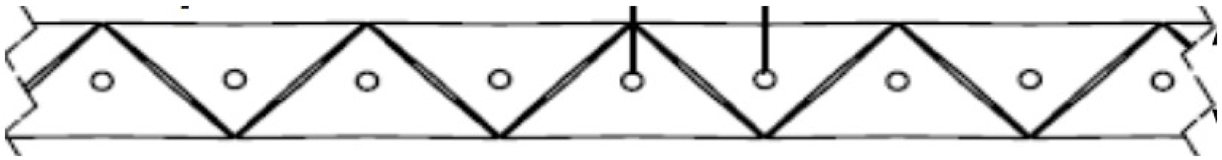
Backup Slides

MINERvA's Detector



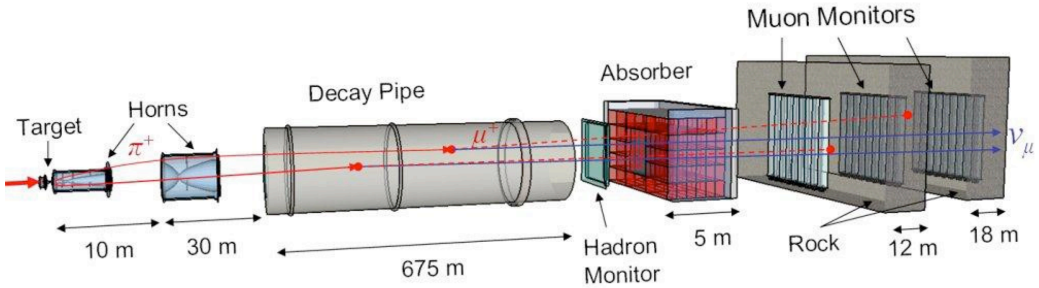
Nucl.Instrum.Meth.A 743 (2014) 130
and beam test
Nucl.Instrum.Meth.A 789 (2015) 28

Three views:
X: Vertical
U,V: $\pm$60

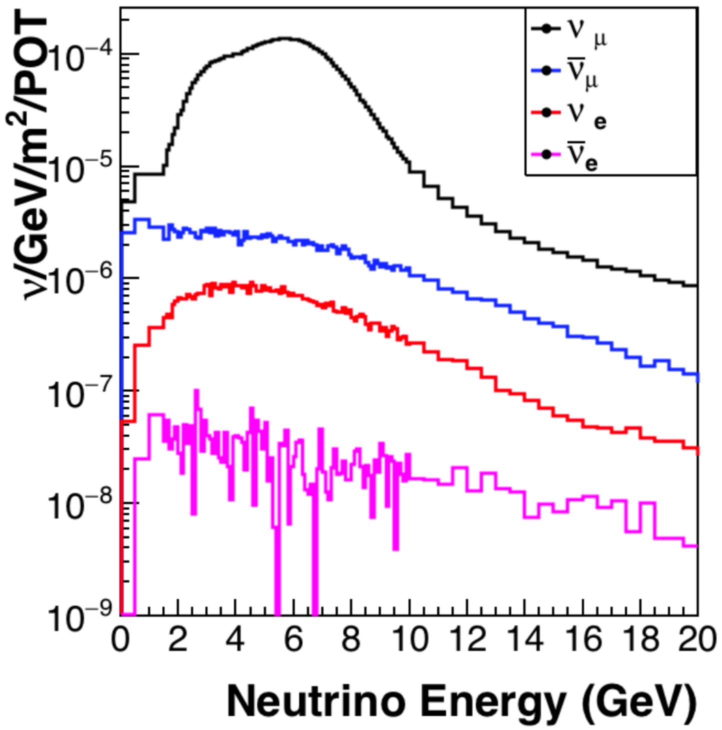


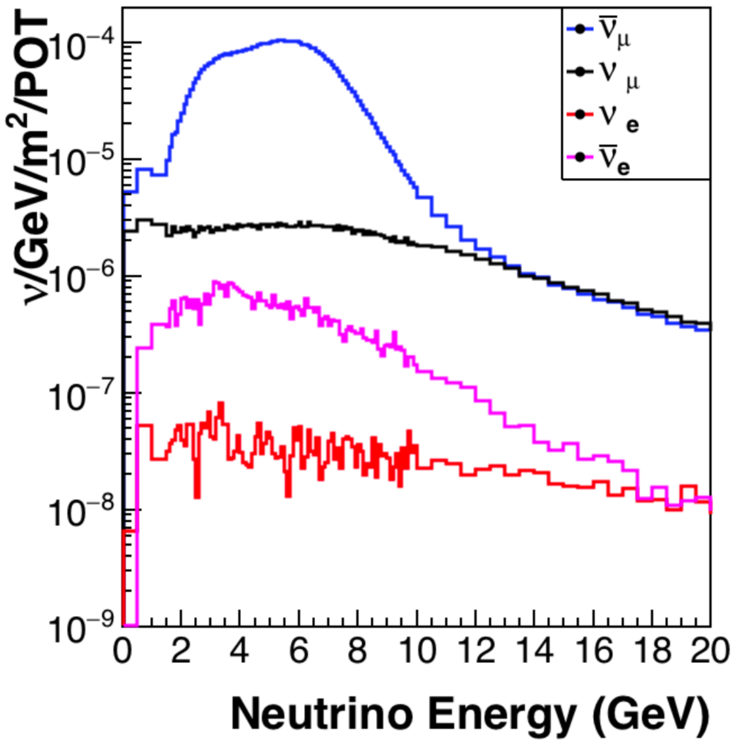
Spatial resolution ~3mm
Timing resolution ~3ns

NuMI Beamline



- Well-understood beam thanks to ν-e scattering constraints, Hadron Production Data, and low-ν shape constraint





L. Zazueta et al., Phys.Rev.D 107 (2023) 1, 012001
D. Ruterbories et al., Phys.Rev.D 104 (2021) 9, 092010
A. Bashyal et al., JINST 16 (2021) P08068
E. Valencia et al., Phys. Rev. D 100, 092001 (2019).
L. Aliaga, M. Kordosky, T. Golan et al, Phys. Rev. D 94, 092005

Graphic from arXiv:2312.16631 [hep-ex]

Relationship between KE and Distance

- Left plot: fit to the peak pion kinetic energy for each measured pion range in mm
- Note threshold well below tracking threshold of 35MeV